Induced decay of composite $J^{PC}=1^{++}$ particles in atomic Coulomb fields

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The electron-positron pairs observed in heavy-ion collisions at Gesellschaft für Schwerionenforschung Darmstadt mbH have been interpreted as the decay products of yet unknown particles with masses around 1.8 MeV. The negative results of resonant Bhabha scattering experiments, however, do not support such an interpretation. Therefore we focus on a more complex decay scenario, where the e^+e^- lines result from a two-collision process. We discuss the induced decay of a metastable 1^{++} state into e^+e^- pairs. For most realizations of a 1^{++} state such a decay in leading order can only take place in the Coulomb field of a target atom. This fact has the attractive consequence that for such a state the Bhabha bounds are no longer valid. However, the absolute value of the e^+e^- production cross section turns out to be unacceptably small.

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For a number of years the Gesellschaft für Schwerionenforschung Darmstadt mbH (GSI) e^+e^- lines have posed a vexing problem. Hardly anybody expects really new physics, such as new particles or novel types of resonances, in the energy range of a few MeV. However, a satisfactory conventional explanation of the anomalous e^+e^- coincidences observed in heavy-ion collisions at GSI is still lacking in spite of numerous experimental and theoretical efforts to explain them, e.g., as due to conversion processes. Until now a considerable amount of experimental information on these line structures in single positron and correlated electron-positron spectra has been collected by the EPOS and ORANGE groups at GSI with different experimental setups and the existence of the observed structures seems to be a well established fact [1,2]. Presently the phenomenon is also studied by an independent experimental group at the APEX facility at Argonne National Laboratory [3].

In this contribution we discuss a particle decay scenario which gives interesting relations between particle decay in high-Z and low-Z media. A particle decaying into an e^+e^- pair seemed to be a natural explanation of the observed coincidences. However, it soon became clear that the decaying particle could not be an elementary one. This was ruled out, e.g., by the nonobservation of e^+e^- decays in high-energy beam dump experiments [4]. All efforts to save the particle hypothesis in terms of composite particle models failed due to the negative results of low-energy Bhabha scattering. See, however, [5]. One possible exception is the proposal by Spence and Vary [6], who argued that the decay width might strongly depend on the surrounding Coulomb field. It will turn out that the scenario we propose actually realizes this possibility.

It is natural to assume that a particle decaying in free space into e^+e^- should show up as a resonance in the time-reversed process, i.e., Bhabha scattering [7]. Assuming that the dominant decay channel is the e^+e^- channel, the most sensitive Grenoble measurements rule out all resonances with lifetimes $\tau_X < 10^{-10}$ s, which is the time scale set by the heavy-ion experiments [5,8]. However, the fact that low-Z solid-state targets had to be used may provide a loophole for the particle interpretation as already outlined in [9].

Conventionally one assumes that the particle is created in the fields of the scattered heavy ions and then, traveling with c.m. velocity, decays in free space into e^+e^-. As at least a few lines seem to come from an emitter located at rest in the laboratory system one could discuss an alternative concept. In this scenario, not only the particle creation but also the decay is mediated by the strong fields. In this sense we speak of an induced decay scenario where the particle produced is a highly stable object, annihilated in external fields only (Fig. 1). The whole idea is to find a composite particle state for which the free decay into e^+e^- is naturally suppressed. Our candidate for such a particle has the spin and parity assignment 1^{++} in its ground state, as every conventional 1^{++} state in leading order in α in free space can only decay according to $X^0 \rightarrow e^+e^- + \gamma$, $X^0 \rightarrow 4\gamma$, etc. [10]. Considering the interaction with a target atom, an additional factor Z^2 enters which favors the e^+e^- pair production. Inspired by this observation we discuss the following mechanism. In the heavy-ion experiments the X^0 is produced in various excited states from where it rapidly cascades to the postulated ground state 1^{++}. In a secondary collision with a target atom the 1^{++} decays to the later observed e^+e^- pair. In the Bhabha experi-

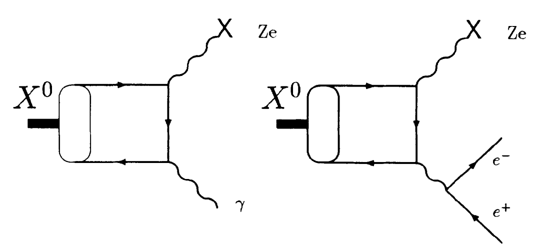

FIG. 1. Feynman diagrams of the induced X^0 annihilation in the field of a target nucleus.

ments the X^0 may be produced in a 1^{--} state via a single photon then undergoing a radiative decay to the 1^{++} state. We then expect the target fields not to be strong enough to induce the e^+e^- decay. However, we shall actually see that the velocity dependence of the cross sections plays an even more important role than the difference between the target materials employed in the heavy-ion and Bhabha experiments. The induced decay scenario described above agrees with earlier suggestions of the ORANGE group. They argued that some of the e^+e^- lines with narrow sum energy and small opening angle might be explained by a two-step process involving a third heavy partner which takes up recoil but no energy [11].

To get some qualitative and quantitative estimates of the process described we make use of a specific composite particle model, the f^+f^- model, which in essence was constructed to allow for a semiquantitative phenomenological description of the data [12,13]. In this model the X^0 is described as a mesonlike object consisting of a pair of charged fermionic constituents f^+f^- confined by yet unknown forces. The wave function is obtained in the framework of a nonrelativistic potential model and the free parameters are fitted to give the ground-state energy and lifetime as required by experiment. We choose the ground state of the object to be the $J^{PC}=1^{++}$ state such that the state cannot decay via a single photon into an e^+e^- pair or into two on-shell photons. The Feynman diagrams for the *induced decay* in the field of a target nucleus are depicted in Fig. 1. The respective cross sections are proportional to $Z^2\alpha^3$ and $Z^2\alpha^4$, respectively, and therefore may be strongly enhanced compared to free decays.

To calculate the cross section for the induced e^+e^- and single-photon decay of a composite particle with four momentum P and mass M we start with the following amplitude ($J=L=S=1$) [14]:

$$A^{JJ_z}_{\mu_{LS}}(P)=\sum_{L_z,S_z}\int[d^3k/(2\pi)^3]\tilde{\psi}_{LL_z}(\mathbf{k})(LSJ|L_zS_zJ_z)\times\mathrm{Tr}[\tilde{O}_\mu(P,\mathbf{k})P_{SS_z}]\ , \tag{1}$$

with

$$\tilde{O}_\mu(P,\mathbf{k})=\{1/[2m_f(m_f+P_0/2)]\}(m_f-\bar{\not p})\times\hat{O}_\mu(P,\mathbf{k})(m_f+\not p)\ , \tag{2}$$

$$P=p+\bar{p}=(P^0,\mathbf{P}),\quad 2k=p-\bar{p}=(0,2\mathbf{k})\ , \tag{3}$$

where $\tilde{\psi}_{LL_z}(\mathbf{k})$ is the Schrödinger wave in momentum space obtained from the nonrelativistic potential model describing a state with definite angular momentum L and projection L_z. P_{SS_z} acts as a spin projection operator [14]. $\hat{O}_\mu$ is a Dirac operator which corresponds to induced annihilation of free f^+f^- pairs of mass m_f with definite momenta $p,\bar{p}$ and spins $s,\bar{s}$. According to the Feynman diagrams (Fig. 2) this is given by

$$\hat{O}_\mu=Ze\tilde{V}(\mathbf{q})\{(-ie\gamma_\mu)[i/(\not p+\not q-m_f+i\epsilon)](-ie\gamma_0)+(-ie\gamma_0)[i/(\not p-\not Q-m_f+i\epsilon)](-ie\gamma_\mu)\}\ , \tag{4}$$

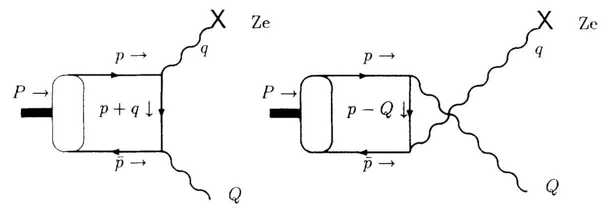

FIG. 2. Feynman diagrams for the induced annihilation of a composite particle state into an off-shell photon.

where the momenta of the Coulomb and of the produced virtual photon are q and Q, respectively. $Ze\tilde{V}(\mathbf{q})$ is the Coulomb potential in the Thomas-Fermi-Molière form to take into account screening effects. To obtain the single-photon annihilation we proceed in the standard way described in [14,15]. For the e^+e^- annihilation a somewhat different approach has to be chosen. We expand the amplitude in powers of $\mathbf{k}$ and retain only the first nonvanishing terms which is justified by the nonrelativistic nature of the bound state. Since P-wave functions vanish at the origin we have to go up to the linear term. The annihilation amplitude is given by

$$A^{JJ_z}_{\mu_{1S}}(P)=-i\sqrt{3/4\pi}[dR_1(0)/dr]\times\sum_{L_z,S_z}(LSJ|L_zS_zJ_z)\epsilon^j(L_z)(\partial/\partial k^j)\times\mathrm{Tr}[\tilde{O}_\mu(P,\mathbf{k})P_{SS_z}]|_{k^j=0}\ , \tag{5}$$

where $R_1(0)$ is the radial part of the wave function in coordinate space. The denominator of the propagator in the approximation $\mathbf{k}=\mathbf{0}$ reads

$$1/[(P/2-Q)^2-m_f^2]=1/[(M/2)^2-m_f^2-P\cdot Q+Q^2]\ . \tag{6}$$

For the case of a real photon $Q^2=0$ this expression is strictly negative and therefore no divergencies can arise. The derivation of the final single-photon-annihilation cross section is therefore straightforward; however, due to the derivative with respect to the intrinsic momentum k_i the final result is quite complex [16]. For the annihilation into an off-shell photon, subsequently decaying into an e^+e^- pair, the situation is more complicated. We get a divergent amplitude for the kinematical condition:

$$(M/2)^2-m_f^2=P\cdot Q-Q^2=\mathbf{q}\cdot\mathbf{Q}\ . \tag{7}$$

This unphysical behavior can be traced back to the neglect of the intrinsic momentum $\mathbf{k}$. To obtain a physical meaningful result we proceed in a somewhat different manner and perform the k integration over the propagator explicitly while neglecting the $\mathbf{k}$ dependence everywhere else in the trace:

$$I_{LL_z}(K_0,\mathbf{K})=\int\frac{d^3k}{(2\pi)^3}\frac{\tilde{\psi}_{LL_z}(\mathbf{k})}{(P_0/2-Q_0)^2-m_f^2-(\mathbf{P}/2-\mathbf{Q}-\mathbf{k})^2+i\epsilon}=\int\frac{d^3k}{(2\pi)^3}\tilde{\psi}_{LL_z}(\mathbf{k})\tilde{\Delta}_F(K_0,\mathbf{K}-\mathbf{k})\ , \tag{8}$$

with $K=P/2-Q=(K^0,\mathbf{K})$ and the Klein-Gordon propagator

$$\tilde{\Delta}_F(K_0,\mathbf{K}-\mathbf{k})=\int d^3x\,\Delta_F(K_0,\mathbf{x})\exp[i(\mathbf{K}-\mathbf{k})\cdot\mathbf{x}]\ .$$

Performing a contour integration over k we obtain

$$I_{1\pm1}(K_0,\mathbf{K})=\mp iF_1(K^0,|\mathbf{K}|)\sin\vartheta_K\exp(\pm i\varphi_K)\ , \tag{9}$$

$$F_1(K^0,|\mathbf{K}|)=\sqrt{3/8\pi}\int_0^\infty dx\,xj_1(Kx)R_1(x)\times\exp(-i\sqrt{K_0^2-m_f^2}x)\ . \tag{10}$$

All angles are measured with respect to the momentum vector $\mathbf{P}$ of the incoming X^0, which was chosen as quantization axis. The expression (10) is to be inserted in (1). For convenience we restrict ourself to the $J_z=0$ polarization state since e^+e^- annihilation rates differ negligibly for different polarizations. Contracting the squared amplitude with the lepton tensor and inserting flux factors and wave-function normalization factors we obtain the final $X^0(1^{++})+(\mathbf{E},\mathbf{B})\rightarrow e^+e^-$ cross section in the laboratory system

$$\sigma_{e^+e^-}(P)=\{Z^2\alpha^4\tilde{M}^4/[6\pi|\mathbf{v}|(m_f+P^0/2)^2]\}\int_0^{P_0^2-4m_e^2}dQ^2\int_{-1}^{1}d\cos\vartheta_Q[|\mathbf{Q}|\tilde{V}(\mathbf{q})^2/Q^2]\sin^2\vartheta_K|F_1(K^0,\mathbf{K})|^2\times(1+2m_e^2/Q^2)(\sqrt{1-4m_e^2/Q^2}) \tag{11}$$

with the abbreviation $\tilde{M}^2=4P_0m_f+M^2+4m_f^2$.

Figure 3 shows the dependence of the scaled annihilation cross sections $\tilde{\sigma}=\sigma/Z^2$ on the total energy of the X^0. Whereas $\sigma_{e^+e^-}$ decreases with rising X^0 velocity, σ_γ shows the opposite behavior. As mentioned earlier, in the case of the single-photon annihilation the virtual fermion is offshell, but it becomes almost real in the limit $v\rightarrow c$. Therefore the amplitude is enhanced in this region and hence the cross section rises despite the flux factor $1/v$.

Free X^0 decays are characterized by a back-to-back emission (in the rest frame) of the lepton pair. The momentum transfer to the target atom will change the angular correlation. To get an estimate of the deviation from the back-to-back characteristic, we calculate the expectation value of the squared recoil momentum:

$$\langle\mathbf{q}^2\rangle=\int\mathbf{q}^2d\sigma\Big/\int d\sigma\ . \tag{12}$$

As can be seen in Fig. 4 the free decay characteristic becomes more and more disturbed for faster moving particles. Again a drastic difference between the momentum transfer for e^+e^- annihilation and γ annihilation occurs. The decrease in momentum transfer for higher velocities reflects the fact that no momentum transfer is required to fulfill the on-shell condition $Q^2=0$ in the limit $v\rightarrow c$.

The Bhabha scattering experiments are characterized by the use of low-Z targets ($Z=4$) and high velocity ($v=0.83c$) of the particle produced at resonance. The hypothetical particle in heavy-ion collisions is expected to travel with low velocity ($v\approx0.05-0.1c$) whereas the target Z is very high ($Z=92$). Employing these numbers in Eq. (11) we get a cross-section ratio:

$$\sigma_{\rm GSI}(1^{++}\rightarrow e^+e^-)/\sigma_{\rm Bhabha}(1^{++}\rightarrow e^+e^-)\approx1\times10^6\ . \tag{13}$$

These cross sections only refer to the *decay* of the particle in a secondary collision. There will be also a suppression of $X^0(1^{++})$ *production* in Bhabha scattering since this state cannot be directly reached by e^+e^- annihilation. Also, the competing single-photon channel, negligible for GSI experiments would play a significant role for the Grenoble setup, only $\frac{1}{3}$ of the X^0 would decay in e^+e^-. Moreover the free Bhabha kinematics is heavily disturbed due to the large momentum transfer $\langle\mathbf{q}^2\rangle^{1/2}\approx770$ keV hiding the resonance from detection. Therefore we can conclude that if the GSI lines are the result of an induced decay of a yet unknown 1^{++} state, it is impossible to detect the particle in resonant Bhabha scattering. While this qualitative property is very encouraging, it seems to

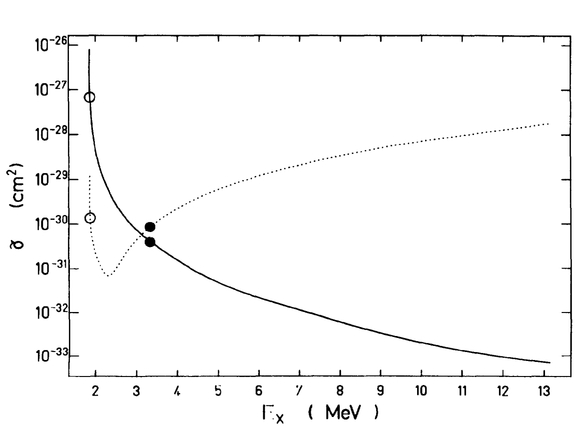

FIG. 3. Scaled total cross sections $\tilde{\sigma}=\sigma/Z^2$ of the induced e^+e^- annihilation (full line) and the induced single-photon annihilation (dotted line) as function of the total X^0 energy E_X. (○, GSI experiment; ●, Bhabha experiment.)

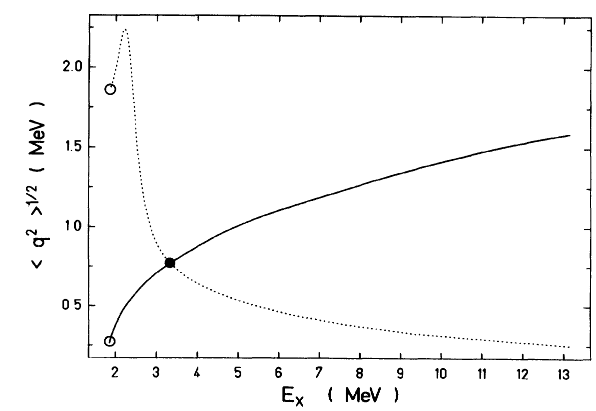

FIG. 4. The expectation value of momentum transfer to the target atom for the induced e^+e^- annihilation (full line) and the induced single-photon annihilation (dotted line) as function of the total X^0 energy E_X. (○, GSI experiment; ●, Bhabha experiment.)

be difficult to get quantitative agreement. The quantitative results are given in Table I. The momentum transfer $\langle \mathbf{q}^2 \rangle^{1/2}_{e^+e^-} \approx 300$ keV is to be compared with the results of the ORANGE group, who noted that the target recoil momentum appears to be of the order of 800–1000 keV for the 635-keV line observed for U+Ta collisions and the 555-keV line observed for U+U collisions. However, the proposed two-step mechanism only can work if the cross section for the induced pair decay is large enough so that a significant fraction of the particles can decay within the target foil. For the 380-μg/cm^2 U target employed at GSI this would call for a cross section $\sigma_{e^+e^-} > 10^{-18}$ cm^2, 5–6 orders of magnitude larger than what we get from our model. We remark that the corresponding cross section necessary to observe the induced decay in the Grenoble Bhabha experiment using the 4.6-mg/cm^2 Be target is $\sigma_{e^+e^-} > 10^{-20}$ cm^2.

The qualitative results in principle should be independent of the employed wave function since they are governed by the pole behavior of the fermion propagator and thus by the special kinematics of our process. Thus we expect the f^+f^- model to be quite representative for any composite particle participating in such a two-step process. If so, one would have to conclude that induced particle decay cannot explain the e^+e^- puzzle.

On the other hand, if new experiments support the particle scenario, the induced 1^{++} decay would be a promising candidate to avoid contradictions with Bhabha scattering. Then one has to speculate how it might be possible to enhance the absolute values. First, the $X^0(1^{++})$ production rates in heavy-ion collisions might be large enough to surmount the smallness of the $1^{++} \to e^+e^-$ cross section. This possibility is easily tested by varying the target thickness, on which the e^+e^- rates then should strongly depend. Second, the 1^{++} model parameters might be adjusted as to enlarge the e^+e^- annihilation cross sections. However, this may give rise to unacceptable 1^{++} contributions to QED precision tests, e.g., to $(g-2)$ experiments and therefore potentially can be ruled out in this way.

TABLE I. Cross sections and mean momentum transfers for the induced 1^{++} decay as calculated in our model. The numbers on the left refer to the Z and β values expected in the GSI heavy-ion experiment, the numbers on the right to the respective numbers in the Grenoble Bhabha measurement.

Quantity	$Z=92,\beta=0.1$	$Z=4,\beta=0.83$
$\sigma_{e^+e^-}$	5.7×10^{-24} cm^2	6.3×10^{-30} cm^2
σ_γ	1.2×10^{-26} cm^2	1.4×10^{-29} cm^2
$\langle \mathbf{q}^2 \rangle^{1/2}_{e^+e^-}$	0.274 MeV	0.772 MeV
$\langle \mathbf{q}^2 \rangle^{1/2}_{\gamma}$	1.860 MeV	0.774 MeV

We summarize as follows. Induced decay processes turn out to be practically invisible in Bhabha scattering. The described process could serve as a realization of the two-step process suggested by the ORANGE group, who observed a rather hard recoil momentum of order 800 keV, a number which is larger than our result, but in view of the large error bars of the experiments is not completely incompatible with the 1^{++} decay scenario. However, the predicted cross section for the induced decay is much too small to explain the experiments.

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